Spatial Correlation Function of Soft X-ray Selected AGN

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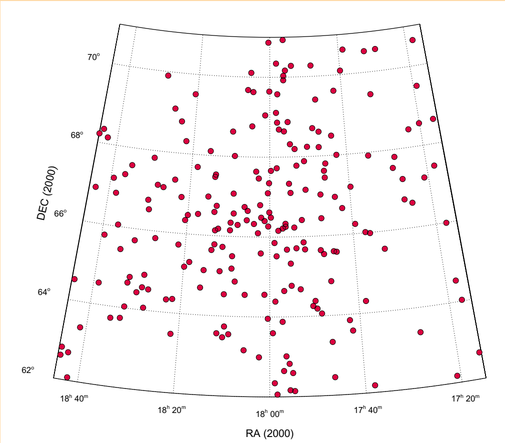

Figure 2 – Distribution on the sky of the 218 AGN in the ROSAT NEP Survey.

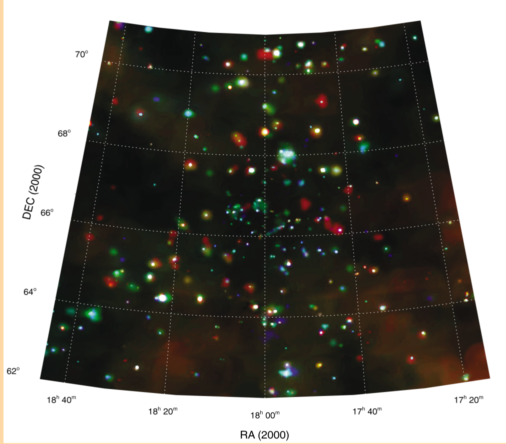

***Figure 1** – ROSAT X-ray color image of the NEP region. The colors mostly encode the X-ray energy with red and yellow for 0.1-0.4 keV, green for 0.4-1.0 keV, and blue and purple for 1.0-2.4 keV photons. White implies bright sources in the 0.4-1.0 and/or 1.5-2.4 keV bands. Note that only the brighter two-thirds of the NEP sources are apparent in this particular image.*

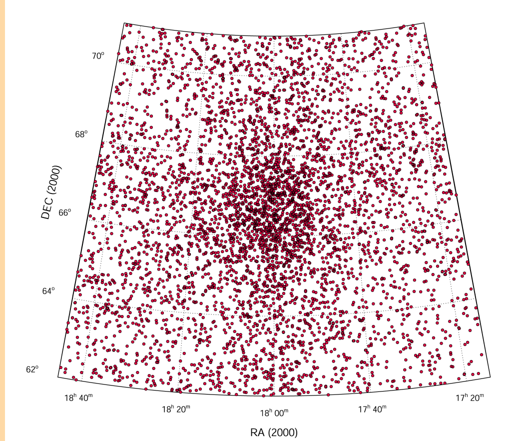

***Figure 5** – Distribution on the sky of 5,000 simulated AGN randomly sampled from the ROSAT NEP Survey using the boundary conditions and selection function of the survey. Source density increases towards the field center (NEP) due to the strongly peaked exposure map.*

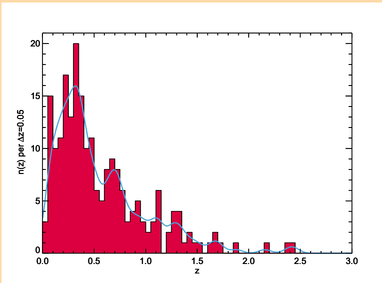

***Figure 3** – Redshift distribution for the ROSAT NEP AGN. The median redshift of the sample is z=0.41. The blue line is the distribution smoothed with a Gaussian of width δz=0.06.*

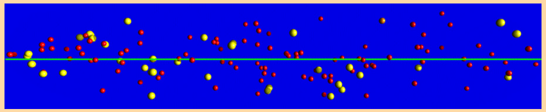

***Figure 4** – Three-dimensional view of the ROSAT NEP Survey volume in comoving space centered on z=0.34 and bounded by z=0.17 on the left and z=0.57 on the right. Red spheres represent AGN while yellow spheres represent galaxy clusters. The green line is the redshift axis pointed towards the NEP. This figure is taken from an animated "fly-through" of the NEP Survey volume which is available at* http://www.eso.org/~cmullis/research/nep3d.html.

Introduction

The clustering properties of AGN encode information on the large-scale structure of the Universe. The spatial correlation function, $\xi(s)$, is a measure of the fractional excess of AGN pairs relative to the random expectation as a function of comoving separation s (Peebles 1980). The shape and amplitude of the correlation function are determined by the distribution of matter fluctuations in the Universe and complex processes related to AGN formation. Note the former is dependent on the initial spectrum of density fluctuations and the development of structure via gravitational instability.

Since the first detection of AGN clustering (Shaver 1984), significant progress has been made in characterizing the phenomenon, particularly at optical wavelengths (see Croom et al. 2001 and references therein). The observed correlation function is usually parameterized by a power law of the form $\xi(s)=(s/s_0)^{-\gamma}$ where the slope is typically $\gamma\sim1.8$. In general, the correlation scale length in redshift-space is $s_0 \sim 6\ h^{-1}$ Mpc, which is similar to the value associated with normal galaxies, but there is considerable disagreement on the evolution of the correlation strength with redshift.

By comparison, the clustering properties of X-ray selected AGN have been largely unexplored and poorly constrained. X-ray emission appears to be a universal feature of AGN (Elvis et al. 1978), and essentially all optically selected AGN are X-ray luminous (Avni & Tananbaum 1986). Thus AGN detected in soft X-rays probably represent a random sampling of the optical population. However, the lack of a detailed understanding of galaxy and AGN formation, and their inter-relationship, motivates an assessment of the populations at all possible wavelengths. Furthermore, X-ray selected samples provide an opportunity to measure the correlation function at low redshifts which complement the high-redshift determinations from optical studies.

Only three clustering studies of X-ray selected AGN exist in the literature (Boyle & Mo 1993, Carrera et al. 1998, Tesch 2000). They report limited clustering significances ($<2\sigma$) and do not jointly constrain s_0 and γ. We report here a new measurement of the correlation function of soft X-ray selected AGN using data from *ROSAT*.

The *ROSAT* NEP Survey

In the *ROSAT* All-Sky Survey, an 80.7 deg^2 region around the north ecliptic pole (NEP) constitutes the deepest observation of the X-ray sky ever achieved with such a large, contiguous solid angle (Figure 1). Here 445 unique sources are detected with fluxes measured at greater than 4σ significance. We have identified the physical nature of 443 (99.6%) of the *ROSAT* NEP X-ray sources through a comprehensive program of imaging and spectroscopy. AGN are the dominant constituents comprising nearly half (49.0%) of the sample (Mullis et al. 2001, Henry et al. 2001, Gioia et al. 2003).

The *ROSAT* NEP sample of 218 AGN is particularly well suited for a clustering analysis (Figure 2). The AGN are drawn from a contiguous, wide-angle region in the sky sampled to a relatively deep X-ray flux limit (3×10^{-14} erg s^{-1} cm^{-2}, 0.5–2.0 keV). The AGN sample is essentially complete and we have spectroscopically measured redshifts for all of the objects (Figures 3 & 4). Furthermore, the survey selection function is well determined and only a function of X-ray flux.

Measuring the Correlation Function

The correlation function is extracted from the spatial data via a pairwise analysis. In essence, the number of AGN pairs of a given spatial separation in the data are compared to the number of pairs of the same separation from a random catalog. An enhancement of the number of data-data pairs relative to the corresponding random-random pairs is indicative of structure in the data. The random catalog is created using a Monte-Carlo technique which homogeneously populates the survey volume in a manner that is consistent with the selection function and boundary conditions of the survey (Figure 5). The population of random AGN has the same physical properties as the observed sample. Fluxes are assigned in accordance with the observed logN(>S)-logS relation, and redshifts are drawn from a probability density function based on the observed redshift distribution smoothed with a Gaussian kernel (blue line in Figure 3). "Simulated" AGN are accepted into the random catalog if their fluxes lie above the local survey limit as judged from a map of limiting fluxes. The random catalog used in our analysis consists of 40,000 objects. We compute the correlation function using the minimum variance estimator suggested by Landy & Szalay (1993), and use a maximum likelihood (ML) method for determining the best power-law fit to the observed correlation function.

Results

We present the spatial correlation function for the *ROSAT* NEP AGN in Figure 6. Clustering is detected at the $\sim4\sigma$ level, and the median redshift of the AGN-AGN pairs at $r < 60\ h^{-1}$ Mpc is z = 0.22. The power-law fit over the range from 4 to 60 h^{-1} Mpc in a Λ-dominated cosmology indicates best-fit values of $s_0 = 7.4\ (+2.5,-3.9)\ h^{-1}$ Mpc and $\gamma = 1.71\ (+0.92,-0.68)$ (Figure 7). If we set $\gamma = 1.8$, the correlation length is $s_0 = 7.5\ (+1.6,-1.7)\ h^{-1}$ Mpc.

Our measurement of the spatial correlation function for soft X-ray selected AGN provides the best constraints reported so far. The derived correlation length is consistent with the value, $s_0 \sim 6\ h^{-1}$ Mpc, associated with normal galaxies and optically selected AGN. This suggests that X-ray luminous AGN are spatially clustered in a manner similar to that of the aforementioned objects. Furthermore, the NEP result is a measure of the local behavior (z ~ 0.2) of AGN clustering, and lends further support to the view that the correlation strength does not evolve strongly with redshift (Figure 8).

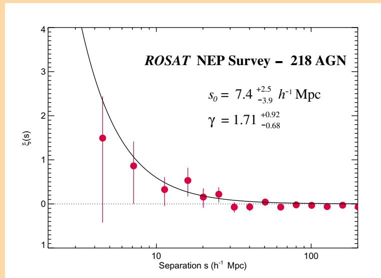

***Figure 6** – Spatial correlation function for ROSAT NEP AGN. These results are derived from the entire sample of 218 objects. The error bars are 1σ Poisson errors and the solid line is a maximum-likelihood power law fit to the range from 4 to 60 h^{-1} Mpc for a Λ-dominated cosmology ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$).*

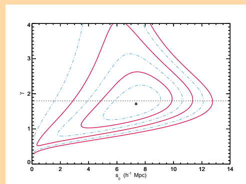

***Figure 7** – Probability contours for the best-fit s_0 and γ parameters from a maximum-likelihood analysis of ROSAT NEP AGN. The contours are the 1σ, 2σ, and 3σ(68.3%, 95.4%, and 99.7%) confidence intervals for two fitting parameters (red) and one fitting parameter (blue). The best-fit parameters are marked by the plus symbol and the horizontal line indicates γ=1.8.*

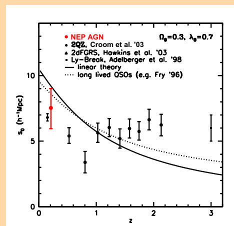

***Figure 8** – The scale length, s_0, of AGN clustering as a function of redshift (adapted from Fig. 2 of Croom et al. 2003).*

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